



The Zero Boil-Off Tank Experiment Contributions to the Development of Cryogenic Fluid Management

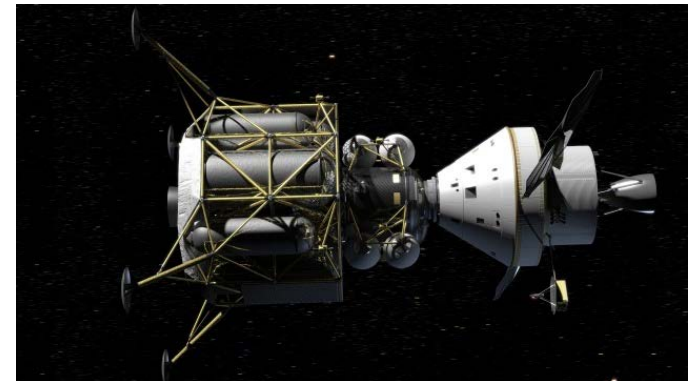
Presentation to
Space Cryogenics Workshop
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NASA Exploration Challenge:

- Reliable cryogenic storage for use in propellant systems is essential to meeting NASA's future exploration goals.
- Heat leaks from surroundings lead to cryogen boil-off and excessive tank pressures.
- Cryogen mass loss occurs when tank is vented
- Predicting boil-off and self-pressurization rates is important.

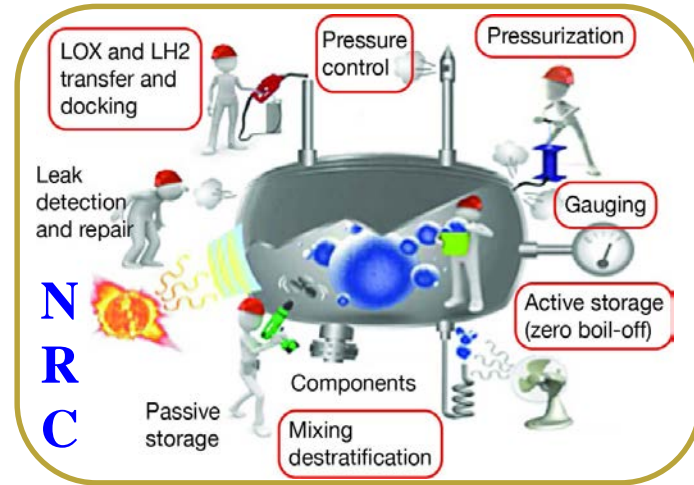


Why Small-Scale Experiment Simulant Fluid?



NRC Decadal Report on CFM:

- “1G empirically-based predictive methods in the design of the future multiphase technologies are of limited use”
- “a new predictive capability and design methodology needs to be adopted that relies in particular on physically-based multiphase models that quantify accurately the effects of gravity.”
- “to be effective, such models must necessarily be assessed against, appropriate small scale reduced-g data, and they must be capable of accurately scaling-up these data to the large multiphase systems for NASA’s future human exploration missions.”



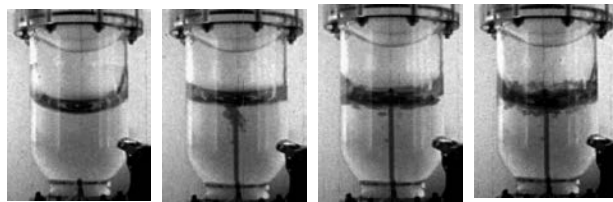
- Controllable BCs -accurate measurements

ZBOT: ➤ Flow visualization & velocimetry

- Extensibility Gap in scale and fluid closed by the model

● **Proposed ISS experiment will be able to bridge ground test extensibility gaps with future mission applications**

Sampling of Prior Work



a) Start b) 0.93 sec c) 2.0 sec d) 3.10

Drop Tower Testing

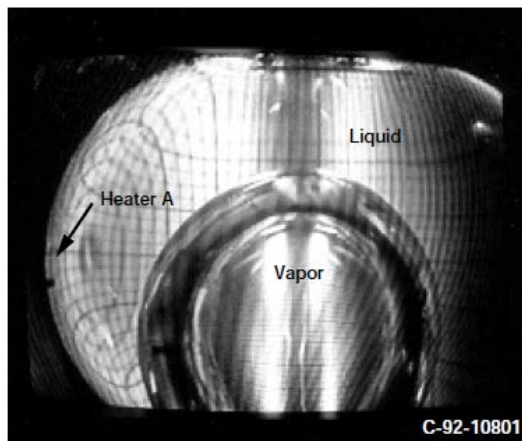


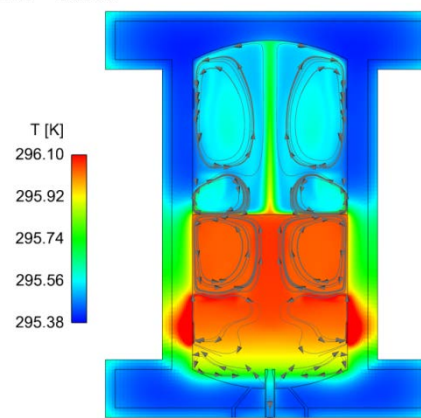
Figure 14.—Actual liquid-vapor configuration during flight experiment.

Tank Pressure Control Experiments 1, 2 and 3

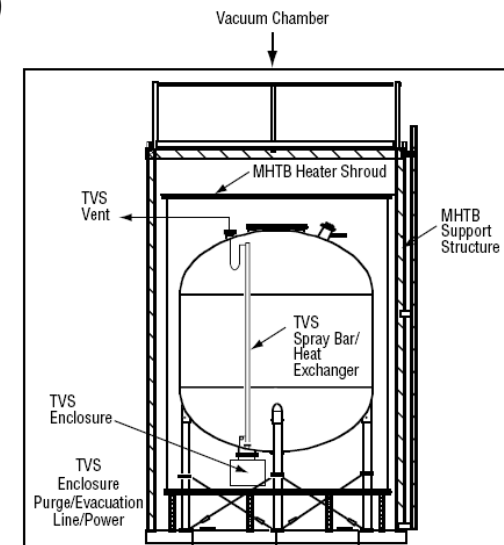
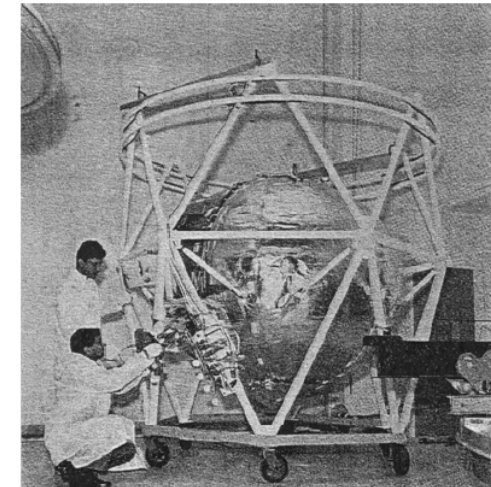


Shuttle Centaur (Un-flown)

Time = 6000s

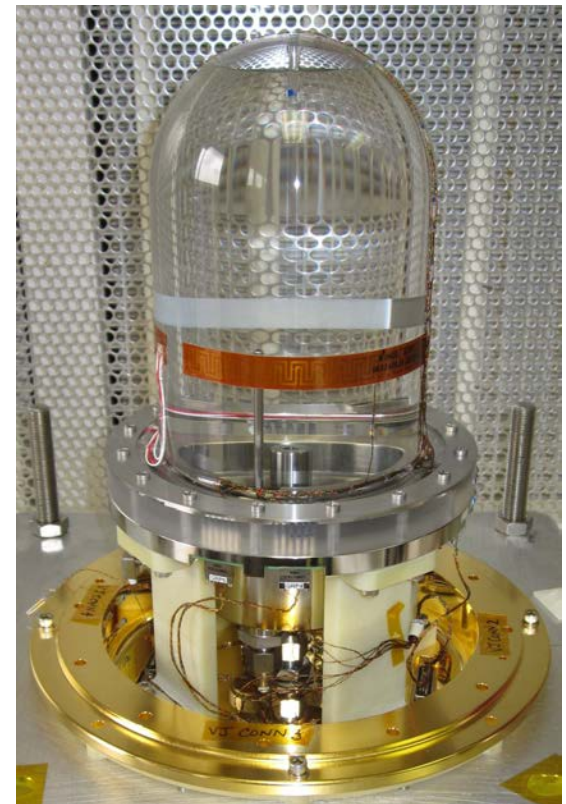


Bench Top Simulant Test and Modeling



Cryogenic Ground Test

- **ZBOT Science Review Panel** composed of six CFM experts from academia, aerospace industry, and NASA laboratories strongly endorsed the objectives of the experiment but recommended that they should be achieved in an incremental manner through a series of experiments with increasing complexity.
 - ✓ **ZBOT-1:**
 - Self-Pressurization, pressure reduction by mixing & destratification
 - Model development and validation
 - **ZBOT-2:**
 - Noncondensable effects on pressurization and pressure control
 - **ZBOT-3:**
 - Different active cooling mechanism
 - Droplet phase change & transport in microgravity
- The follow-on experiments will benefit greatly from heritage developed by ZBOT-1

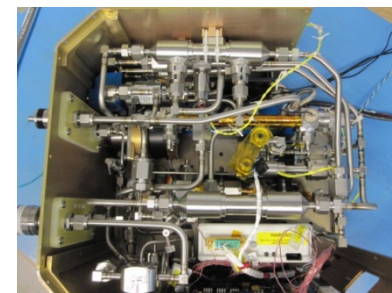
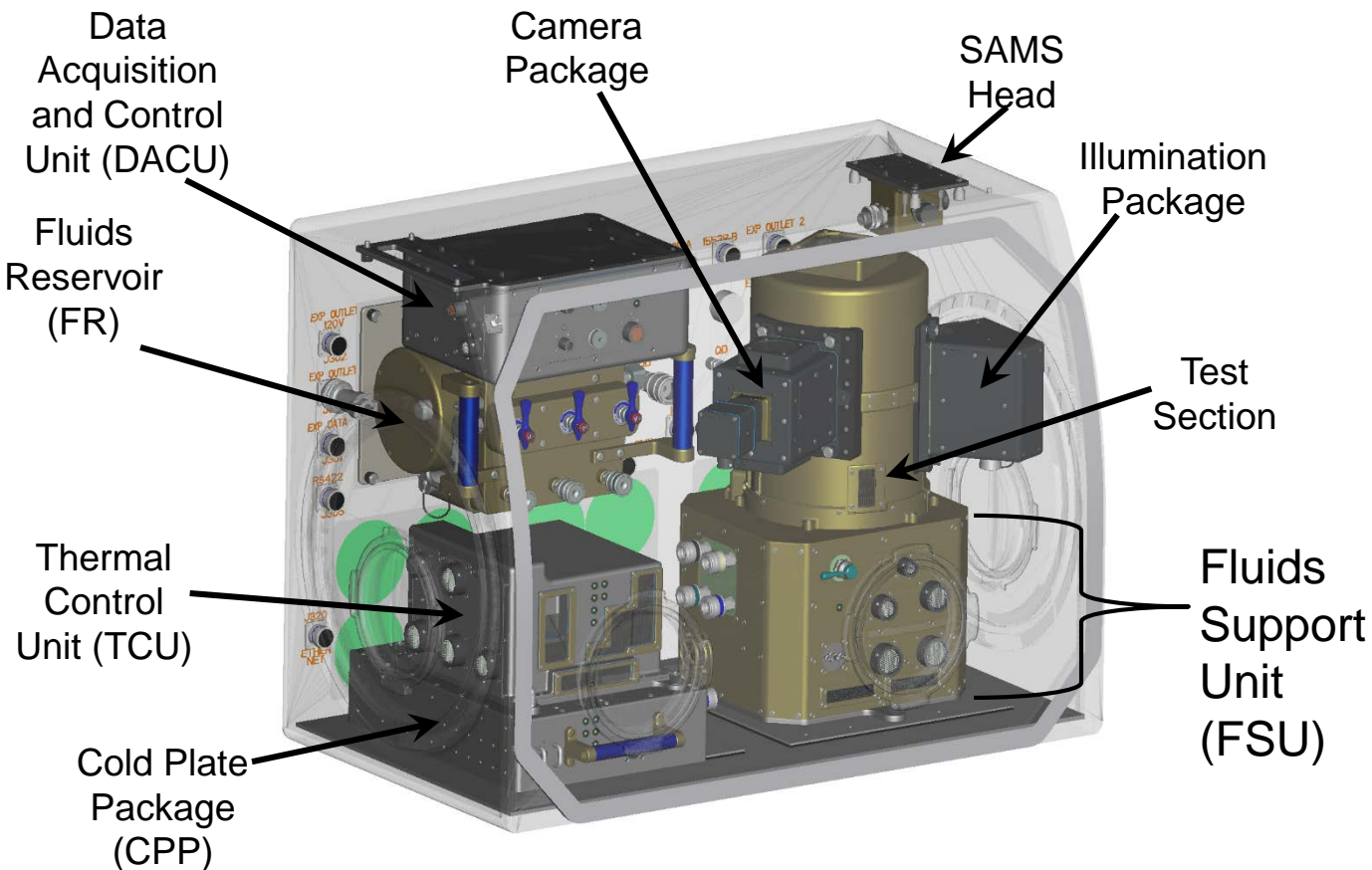


Zero Boil-Off Tank (ZBOT) Experiments

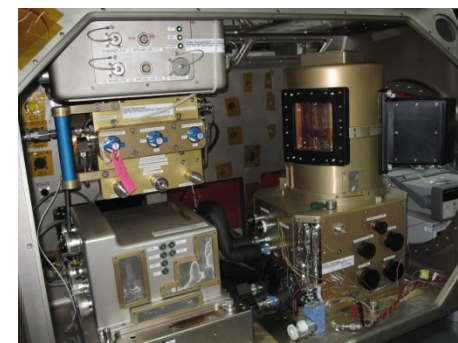


- Investigate innovative storage tank pressure control strategies in microgravity to reduce the cost and increase the reliability of propellant storage tanks for future planetary missions.
- Provide foundation-building microgravity transport & multiphase fluid management data affecting an array of space exploration technologies.
- Develop and validate storage tank CFD models with microgravity reference data to compliment NASA's large scale Cryogenic Fluid Management Efforts.

ZBOT Hardware

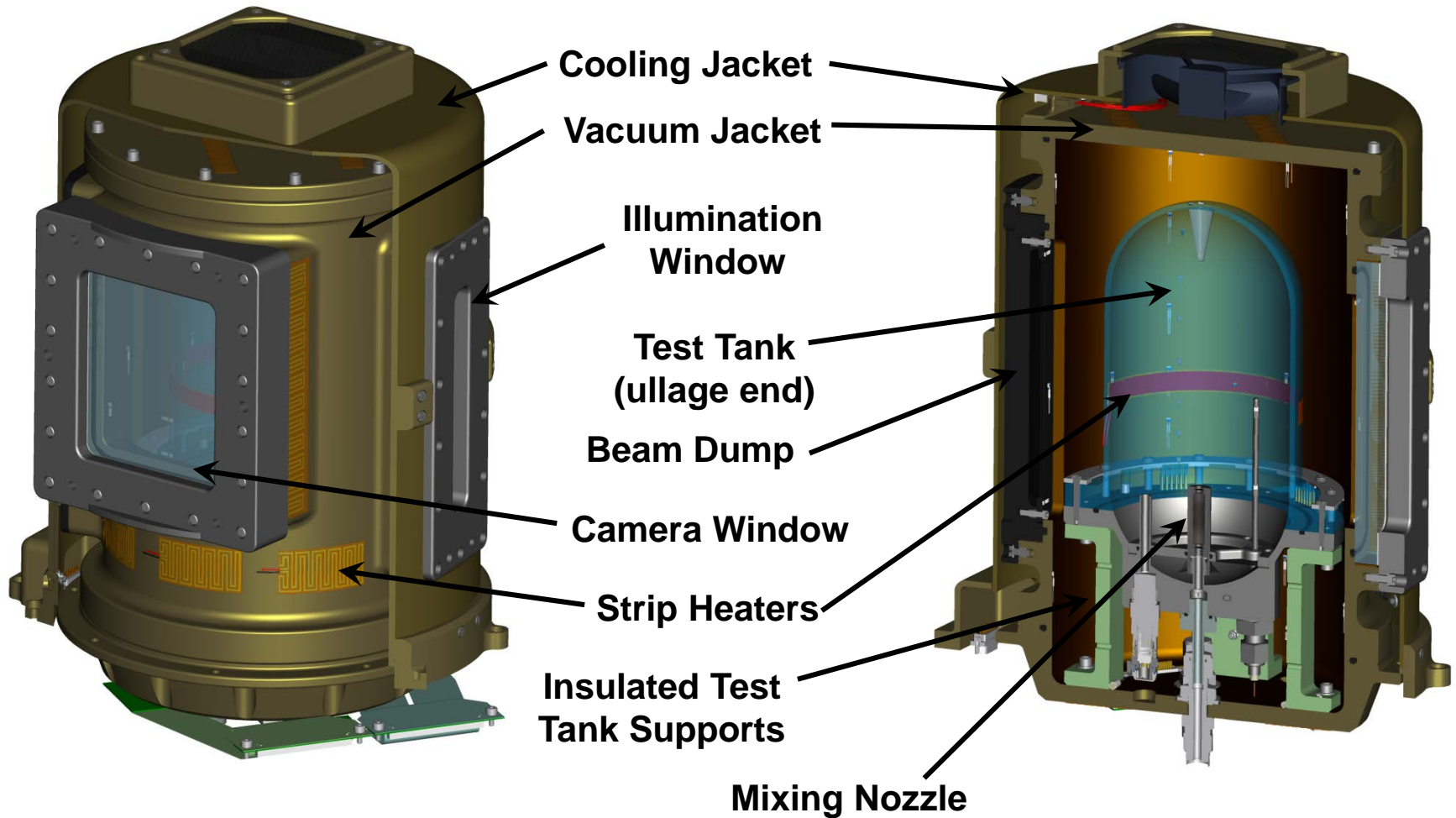


- ZBOT Engineering Model Fluids Support Unit (FSU)

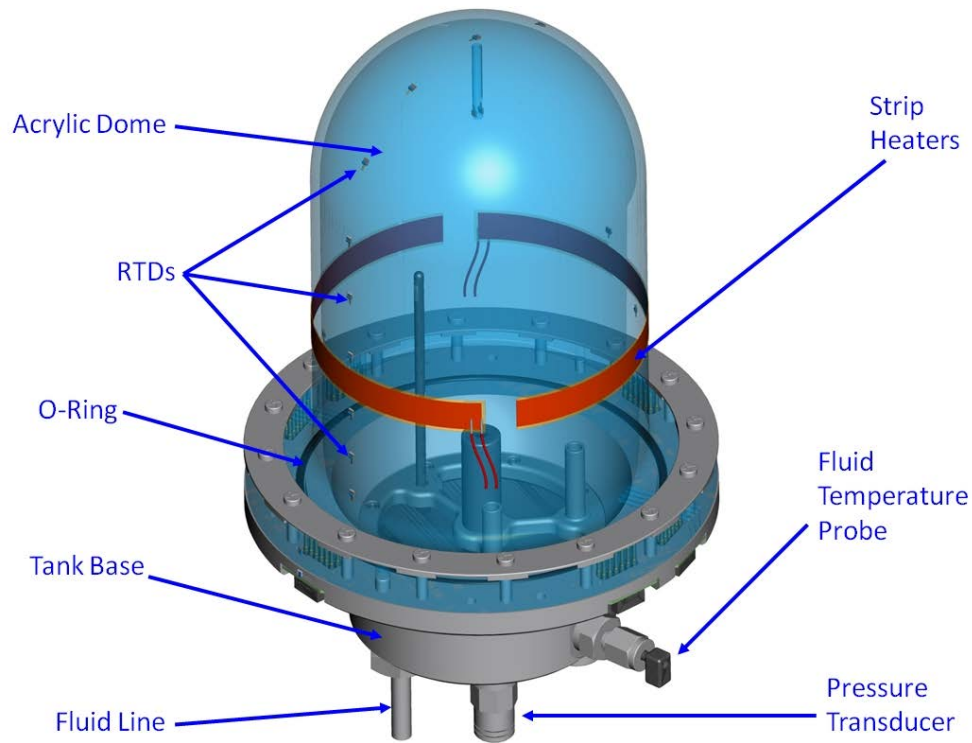


- ZBOT Engineering Model in the Microgravity Science Glovebox (MSG) Work Volume Mockup

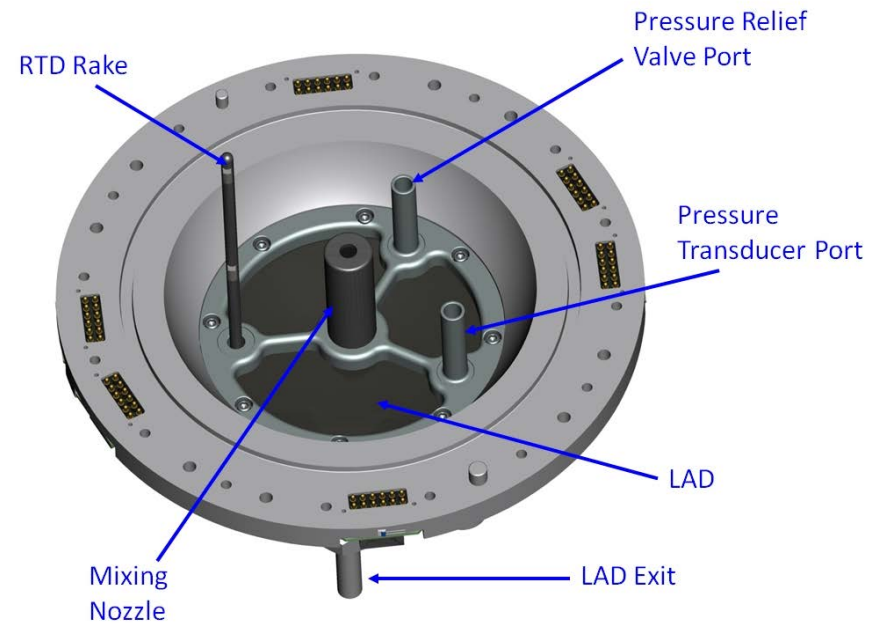
Test Section Subassembly



Test Section – Test Tank



**PMMA (Acrylic)
Test Tank Dome**

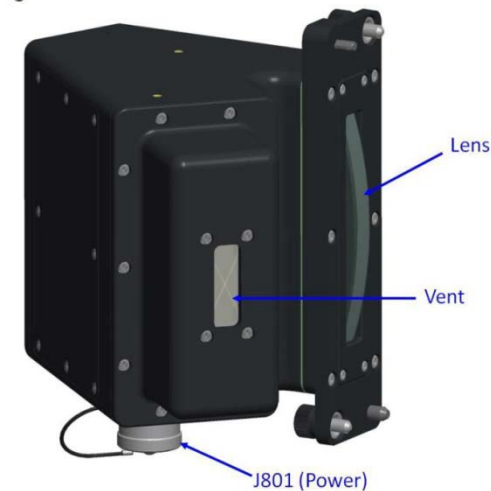
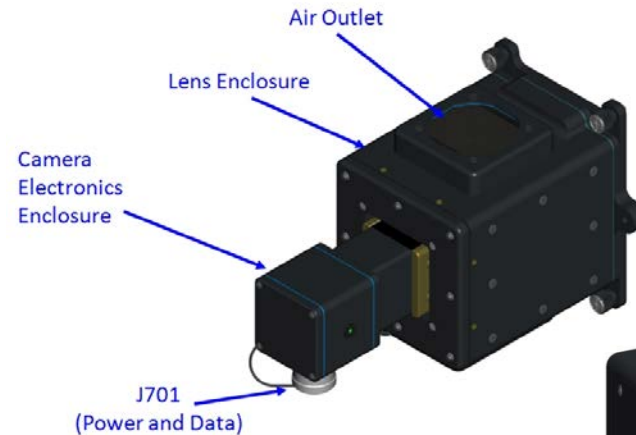


**Stainless Steel Test
Tank Base**

Key Science Instrumentation



- RTDs measure temperatures $20 - 70^{\circ} \text{C} \pm 0.1^{\circ} \text{C}$
- Pressure measured to Maximum Design Pressure of 35 psig $\pm 0.05 \text{ psia}$
- Flow Meter 1 cm/s: $\pm 0.002 \text{ cm/s}$, 25 cm/s: $\pm 0.050 \text{ cm/s}$
- Optically Clear Tank and Camera
- Laser Light Sheet and Particle Injection for Particle Imaging Velocimetry (Demo only)



RTD (uninstalled)

ZBOT Experiment Hardware Concept



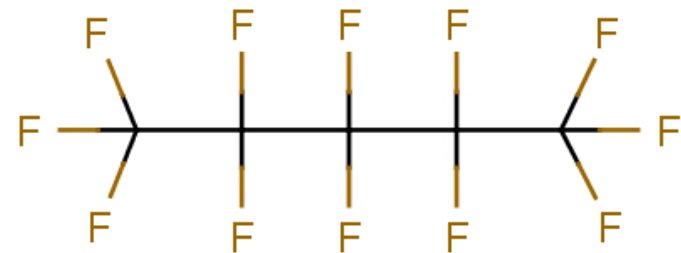
- A transparent test tank houses the model fluid, mixing nozzle, heaters, and diagnostics.
- Thermal conditions are controlled - the test tank is isolated inside a polished vacuum jacket by insulating supports.
- Digital Particle Imaging Velocimetry (DPIV) uses fluorescent melamine resin particles to obtain velocity and flow patterns in the test fluid.
- Resistance Temperature Detectors (RTDs) and pressure transducers provide temperatures and pressures.
- Fluid Support Unit provides flow and fine thermal control of fluid.
- DACU provides control, commanding, telemetry, and data storage.
- Thermal Control Unit provides temperature measurement and control and solenoid valve control
- Cold Plate Package provides power conditioning and fluid heat exchanger for coarse thermal control of the fluid.
- Fluids Reservoir provides fluid storage and fill level control.

Perfluoro-n-Pentane (PnP, or C₅F₁₂)

- High purity (99.7% straight-chained n-isomer)
- Non-flammable, non-toxic, refrigerant/cleaning fluid
- Physical properties
- Boiling Point = 29° C @ 1 atm
- Vapor Pressure = 12.5 psia @ 25° C

Benefits

- Boils Near Room Temperature
- Near zero contact angle with test tank
- Tox 0 – Approved by JSC toxicology and MSFC ECLSS groups as safe for use within International Space Station



PnP n-Isomer (Straight Chained)
Chemical Structure

ZBOT thermal advances from prior art



The ZBOT hardware contains a number of enhancements Including:

- A substantial increase in the number of internal and wall temperature sensors
- The ability to change the tank fill level
- The reduction of all non-condensable gasses to trace levels
- The ability to precisely control the tank enclosure thus both limiting and quantifying the external heat load on the tank
- The ability to precisely control the jet inlet temperature
- Injection into the tank with a known and verified by measurement velocity profile (although this may go away if we remove the flow straightener to help with PIV sticking)
- Significant time between test runs permits well-defined initial conditions to be established for each test run



- How much natural mixing will take place in a given tank during operation at various gravitational levels?
- How much forced mixing is needed to thermally destratify the tanks without active cooling?
- Under what conditions will it be necessary to augment the thermal destratification through active cooling?
- How effectively do mixing-only and/or mixing-with-active-cooling decrease the pressure reduction times?

Need: reliable engineering correlations for mixing, destratification, and pressure reduction times as functions of relevant tank parameters such as heat leak rates, mixing flow rates, and fill levels

Application: sizing of the pumps, determining forced mixing modes, possible placement of flow control structures, and sizing and implementation of the active cooling mechanisms (TVS, Cryocooler, etc.)

Typical Test Approach

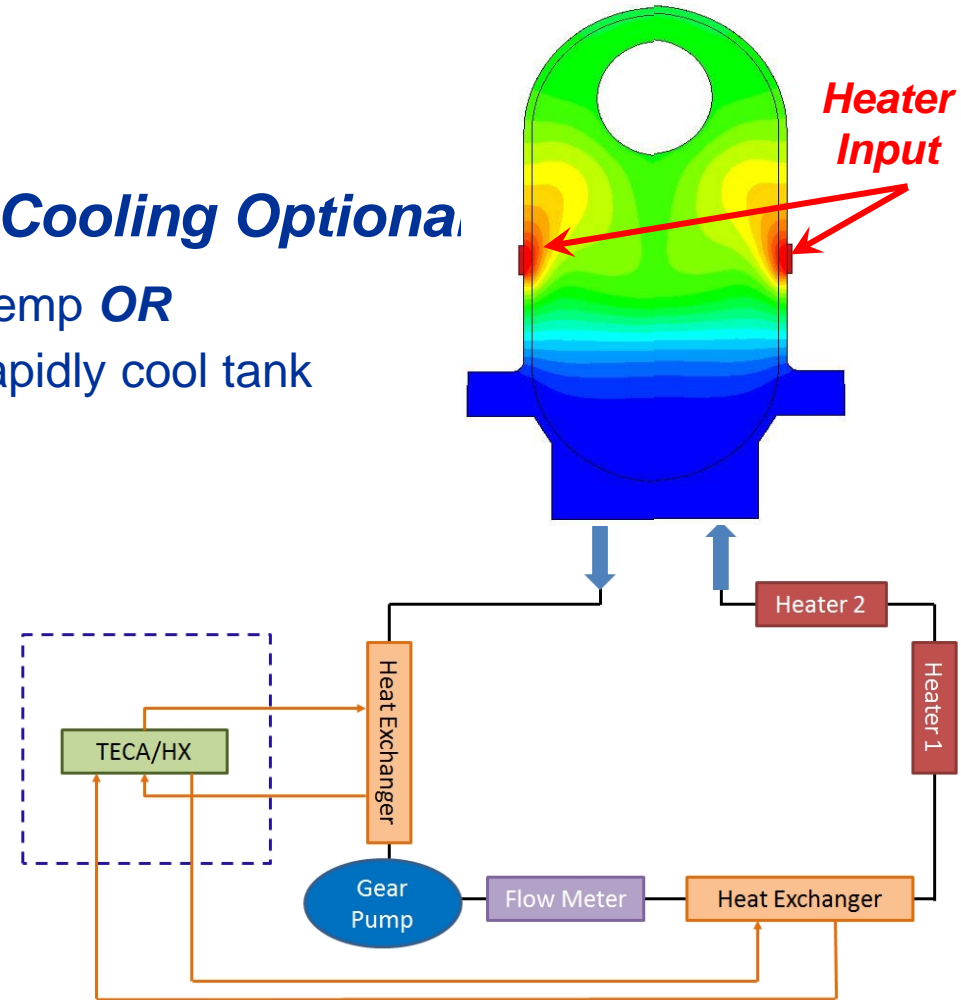
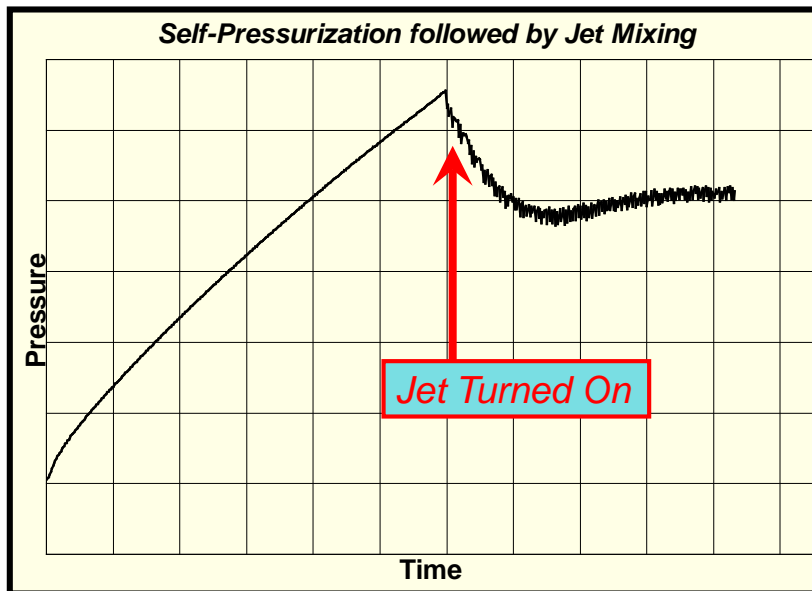


1. Self-Pressurization

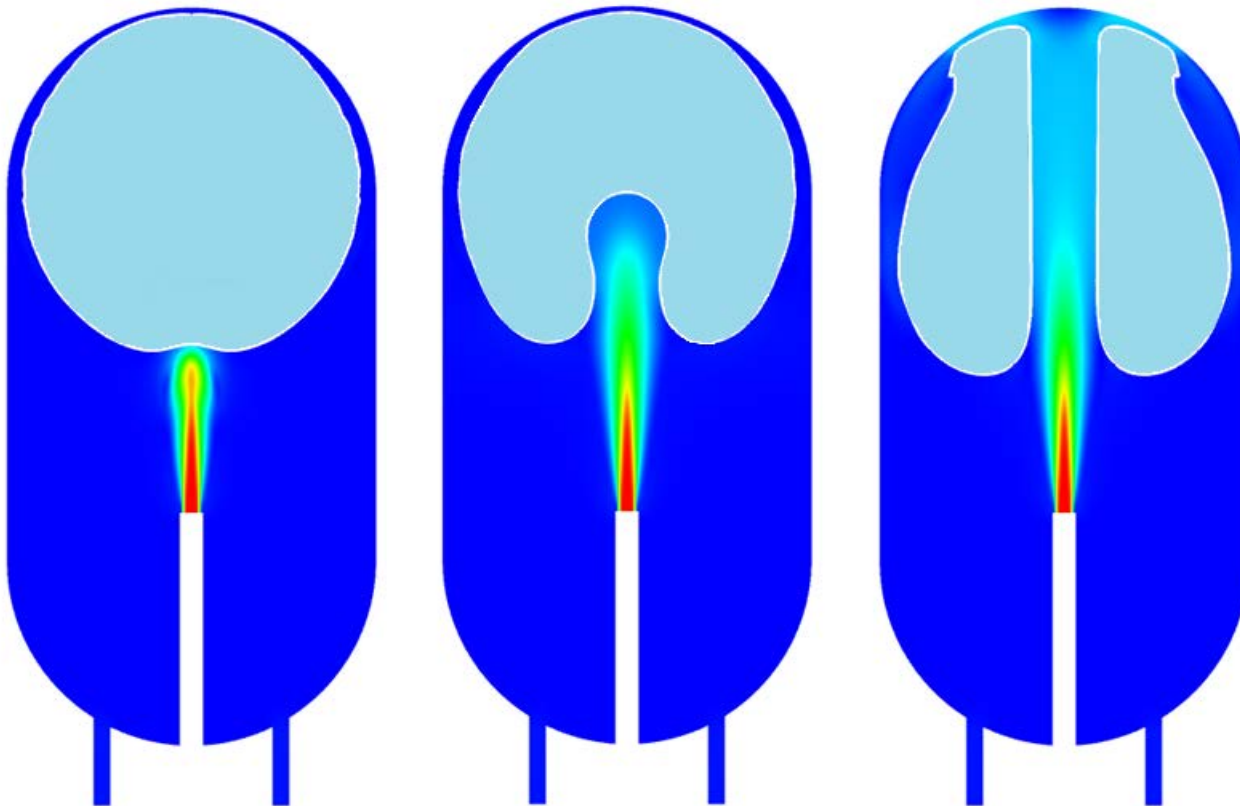
- Heat for 12 hours max.
- Heat at 0.5 to 1.0 Watts

2. Pressure Control via Mixing; Cooling Optiona

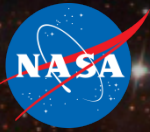
- Mix with inlet temp matched to outlet temp **OR**
- Sub-cooled mixing used after test to rapidly cool tank



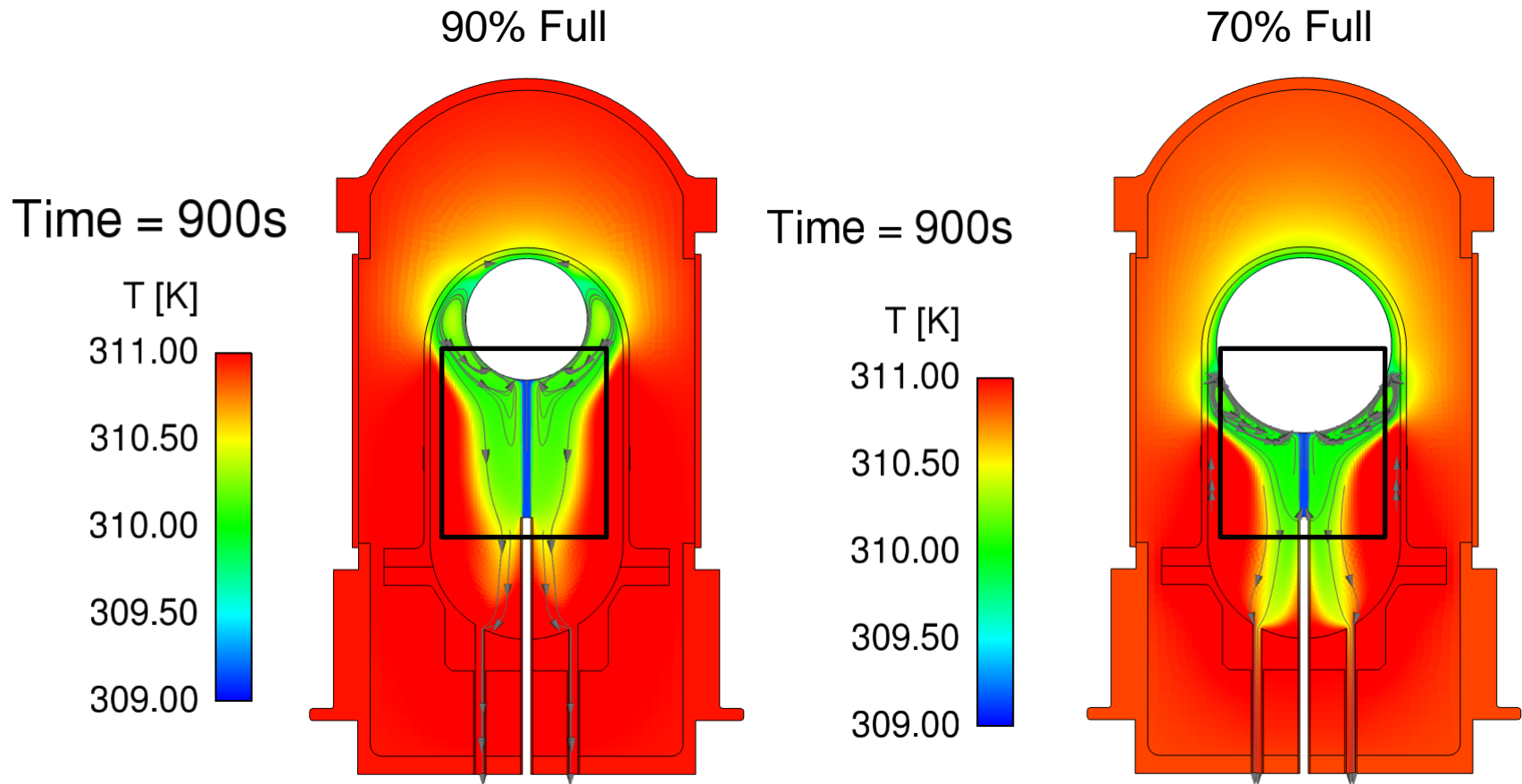
Jet-Ullage Penetration/ Breakup



Heat Transfer Modeling



DPIV Area Marked for 90% & 70% Fill Levels



*Time from start of Axial Jet Mixing

ZBOT ground-based data/model simulations have already produced 10 journal publications (ASME, AIAA, JFM, Cryogenics, IJH&MT), 26 refereed conference papers, 1 PhD dissertation, and 1 Master's thesis

Important Recent Publications have included:

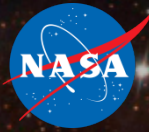
- Barsi S. and Kassemi, M. “Investigation of Tank Pressurization and Pressure Control-Part I: Experimental Study”, ASME Journal of Thermal Science & Engineering Applications, Vol. 5, No 2, pp- 041005: 1-20, December 2013.
- Barsi S. and Kassemi, M. “Investigation of Tank Pressurization and Pressure Control-Part II: Numerical Modelling”, ASME Journal of Thermal Science & Engineering Applications, Vol. 5, No 2, pp- 041006: 1-9, December 2013.
- Mohammad Kassemi, Sonya Hylton, and Olga Kartuzova, Pressurization & Pressure Control in The Zero Boil-Off Tank (ZBOT) Experiment, Ninth International Conference on Two-Phase Systems For Ground and Space Applications, Baltimore, Maryland, USA, September 22-26, 2014
- Kartuzova, O., Kassemi M., Agui, J., Moder, J., “A CFD model for the Multipurpose Hydrogen Test Bed (MHTB) Ground-Based Self-Pressurization and Pressure Control Experiments,” 11th AIAA/ASME Joint Thermophysics and Heat Transfer Conference, AIAA, Atlanta, GA, June 16-20, 2014
- Kartuzova, O., Kassemi M., Agui, J., Moder, J., “Modeling of the Multipurpose Hydrogen Test Bed (MHTB) Self-Pressurization and Spray Bar Mixing Ground-Based (1g) Experiments,” 50th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, AIAA, Cleveland, OH, July 28-30, 2014
- M. Kassemi, S. Hylton, O. Kartuzova, Effect of Residual NonCondensable on Pressurization & Pressure Control of a Zero-Boil-Off Tank in Microgravity, Paper C25-2, 29th Annual Meeting of the American Society for Gravitational and Space Research, , Orlando, Florida, November 2014.
- O. Kartuzova, M. Kassemi, J. Moder, *Modeling Multipurpose Hydrogen Test Bed (MHTB) Self-Pressurization and Spray Bar Mixing Ground-Based (1g) Experiment*, the 48th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, San Jose, CA, July 2013.

Concluding Remarks



- ZBOT is one of a very limited number of opportunities to gather information on low gravity behaviors important to Cryogenic Fluid Management
- ZBOT is nearing final assembly and will fly soon!
- Advance work for ZBOT is already yielding valuable information and advancing the state-of-the-art in modeling Cryogenic Fluid Management

ZBOT Project Team



SCIENCE AND MANAGEMENT

Bill Sheredy– NASA GRC PM
Mohammad Kassemi – PI, NCSE
David Chato - Co-Principal Investigator, NASA

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Sonya Hylton – Research Scientist, NCSE
Bart Gruber – Project Manager, ZIN

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Kimesha Calaway – Systems/Integration, ZIN
Kevin Dendorfer – Electrical Technician, ZIN
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Alex Kieckhafer – Thermal Engineer, ZIN
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John Morrison – Software Engineer
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Brian Loucks– Quality Oversight, ARES

Nechelle Grant - Risk Management, ARES
Rick Plastow– Software QA, Bastion
Chris Bodzioney– Safety Engineer, ZIN
Darryl Seeley – Quality Assurance, ZIN